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SEARCHES FOR NEW PHYSICS

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Current experimental limits for new physics beyond the Standard Model and hints for deviations from Standard Model expectations will be reviewed, highlighting recent results. Possible signals that will be discussed include Higgs bosons, supersymmetric particles, large extra dimensions, new gauge bosons, dynamical symmetry breaking, muon g - 2, rare decays and lepton flavor violation. The discovery potential of the LHC and ILC will be presented, and the impact of discovery on answering fundamental questions of physics will be assessed.

Keywords: new physics; supersymmetry

1. Introduction

This talk is will cover direct and indirect searches for new physics, as well as prospects for the future. Looking at the parallel session agendas reveals the large number of topics to cover: there were 31 talks in the "Direct Searches" session, 10 in "Muon $g-2$, Lepton Flavor Violation and Electric Dipole Moments", 9 in "LHC-LC Comparison" and 43 in non-top "Heavy Flavor Physics". This overview can therefore not be exhaustive, and the author apologizes to all those whose work is not shown here.

2. The Standard Model and Its Caveats

It is sometimes useful to formulate the standard model of particle physics (SM) in words to expose its strengths and weaknesses:

- Matter is built of spin 1/2 particles that interact by exchanging three different kinds of spin 1 particles corresponding to three different (gauge) interactions.
- There are three generations of matter particles.
- The four different matter particles in each generation have different combinations of (quantified) charges characterizing their couplings to the interaction bosons.

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- The matter fermions and the weak interatcion bosons have “mass”. This is called electroweak symmetry breaking (EWSB).
- Gravitation is presumably mediated by spin 2 gravitons.
- There appear to be three macroscopic space dimensions.

The last two items in the list are not strictly speaking part of the standard model, but are generally implicitely assumed.

These very much simplified statements raise a large number of questions. At this particular time, the author considers the following ones to be particularly fundamental:

- What exactly *is* (weak iso)spin? Or color? Or electric charge? Why are they quantified?
- Are there only three generations? If so, why?
- Why is there no matter that doesn’t interact weakly? Or why, for example, are there no neutral, colored fermions?
- What is mass? Is it quantified?
- How does all of this reconcile with gravitation? How many space-time dimensions are there really?
- Is “our universe” the unique solution?

Many other questions can be asked (see for example Ref. [1]). Answering any of these unambiguously at a fundamental level would be a major breakthrough in physics.

3. Mass

Among the fundamental questions cited above, the one we think we have a handle on is mass. The addition of a naïve M^2WW mass term to generate the gauge boson masses (luckily) not only breaks gauge invariance, but also destroys the renormalizability of the standard model. In fact, at high energy ($\sqrt{s} \approx 1.7\ TeV$), W_LW_L scattering violates the Froissard bound. And elegant solution to this problem is provided by the Higgs mechanism: the “standard model Higgs”generates both boson and fermion masses, and “restores” unitarity if $m_H \lesssim 1\ TeV/c^2$.

Since in the standard model the couplings of the Higgs boson to all particles is known, its mass can be inferred from precision measurements that are sensitive to processes in which Higgs bosons contribute at the one- or multiple loop level. This can be seen in Figure 1 [2]: the yellow shaded area is excluded based on direct searches at LEP2 giving $m_H > 114.4\ GeV/c^2$ at 95 % C.L., while the curve is the result of the fit to precision data. It should be noted that this is very sensitive to the measured values of the top quark and W boson mass: the recent increase in the top quark mass [3] by 4 GeV/c^2 has shifted the best fit value up by 18 GeV/c^2. The best fit value is now $m_H = 114\ GeV/c^2$.

If a standard model Higgs boson exists (here standard model denotes that it is the sole source for both the boson and fermion masses), prospects for establishing its existence before the end of the decade are excellent. If it is relatively light, some

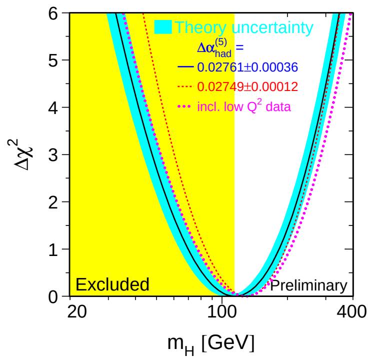

Fig. 1. Higgs boson mass inferred from precision measurements. The yellow shaded area is excluded based on direct searches at LEP2.

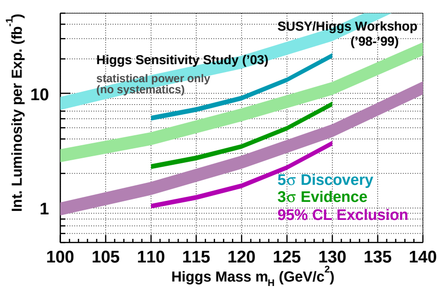

Fig. 2. Tevatron projected sensitivity for Higgs boson discovery as a function of Higgs boson mass and integrated luminosity. The thinner lines are from the 2003 Higgs Sensitivity Study, the thicker from the 1998-1999 SUSY/Higgs Workshop. Current projections estimate that each experiment will receive between 4 and 8 fb^{-1} by 2009.

signal should be visible at the Tevatron [4] before the LHC produces physics results, as can be seen in Figure 2. It should be noted that in this study only the channels in which a Higgs boson is produced in association with a W or Z boson and decays to $b\bar{b}$ have been considered, while at $m_H = 120\ GeV/c^2$, Figure 3 shows that the branching fraction to a pair of W bosons is already quite substantial. This promising channel is actively pursued by both the CDF and DØ collaborations.

In case the standard model Higgs exists, but is too heavy to be seen at the Tevatron, discovery at the LHC within a few years of running is just about certain over the full mass range $100\ GeV/c^2 \leq m_H \leq 1\ TeV/c^2$, as shown in Figure 4 [5].

Discovery of a Higgs boson will be followed by accurate measurement of its properties. Determining that it is indeed the source of all particle masses (i.e. its coupling to the particles), its spin, its self-coupling, etc. will then be key in increasing our understanding of mass as a fundamental property of matter. Measurement of the

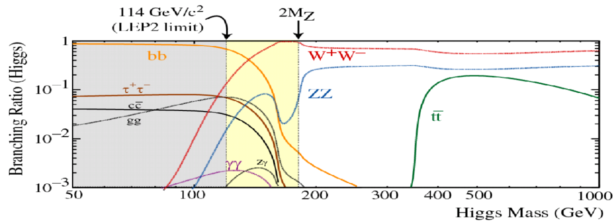

Fig. 3. Standard model Higgs boson branching fractions as a function of its mass.

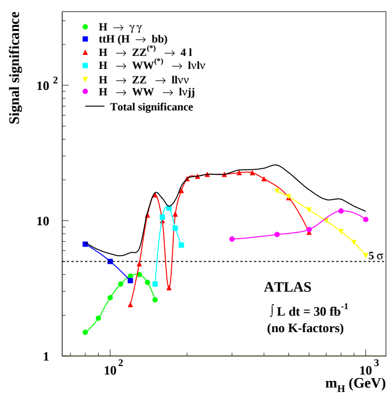

Fig. 4. Sensitivity of the ATLAS experiment for standard model Higgs boson discovery over the full mass range for an integrated luminosity of 30 fb^{-1}, corresponding to three years of low luminosity running. The differently colored lines correspond to different channels. Note that for low masses, the rare $H \to \gamma\gamma$ channel is critical.

couplings to the heavier fermions and the weak bosons can be done through determination of production and decay rates, the former mainly in associated production processes, and the latter limited to decay channels with reasonable rate for a given mass. At the LHC, a few years of low luminosity running can yield measurements at the 10-50% level [6], with best precision on the coupling to W bosons.

The International Linear Collider will then be an ideal place to study the Higgs boson further, and coupling strengths could be measured with precision of better than 1% depending on the Higgs boson mass [7]. The Higgs spin can be verified by measuring the production cross-section as a function of center-of-mass energy [8], although it will probably already have been determined from LHC data (the detection of $H \to \gamma\gamma$ excludes spin 1 as a possibility for example).

4. Models of New Physics

While the discovery of a standard model Higgs boson would represent a significant step forward, it really doesn't tell us what mass is. The question can then be stated as three new, separate questions: why are the Yukawa couplings what they are; why is μ^2 in the Higgs potential negative; and what is the link to gravity?

The Higgs mechanism also introduces a new set of problems (or benefits, depending on one's point of view). The Higgs boson mass is "naturally" the energy scale at which some new physics manifests itself, so if we have a standard model Higgs, that's about 200 GeV. There are two theoretical approaches to accomodate this: fixing by addition (introduction of new particles and - sometimes - interactions with masses $\mathcal{O}(200 - 1000\ GeV/c^2)$ to stabilize the Higgs mass), or fixing by subtraction (no Higgs boson).

4.1. *Low Scale Supersymmetry*

Supersymmetry (SUSY) is certainly the most popular of the existing models, for good reason. In supersymmetry, for each boson there is an associated fermion, and vice-versa. All quantum numbers, except spin, and all couplings are the same for the so-called "superpartners", but their masses appear to be different since none of these "sparticles" have been observed. This is SUSY breaking. As will be shown, low-scale SUSY has a number of attractive features, but one major disadvantage, at least in the author's mind, is that it trivializes spin. So what are the big advantages of SUSY? First, the fermionic and bosonic loop corrections to the Higgs mass cancel each other, so the Higgs boson mass is naturally of the same order as the SUSY mass scale. Second, with the added particles, gauge coupling unification is much improved w.r.t. the standard model [9], in the sense that all three couplings converge in one point just above 10^{16} GeV. Third, SUSY explains EWSB, as will be shown below.

The minimal supersymmetric model means a minimal number of additional particles, but also a minimal number of constraints. This introduces 105 new parameters (sparticle masses, mixing angles, ...). Some searches for superpartners are done in this context, with a very small number of additional assumptions. Typically these are that the Lightest Supersymmetric Particle[a], or LSP, is the lightest neutralino (partners of the neutral bosons mix), and an assumption on the branching fraction for the process studied. Figures 5 and 6 show examples of these performed by the LEP collaborations, CDF and DØ .

Various SUSY breaking models exist, with very different phenomenological signatures, but one general feature is that they demonstrate that supersymmetry can explain electroweak symmetry breaking. This is illustrated in Figure 7 [10]: in supersymmetry, when the renormalization group equations are used to run the couplings down to the electroweak scale, the μ^2 term in the Higgs potential is naturally driven negative, triggering EWSB.

In one of the models, supergravity (SUGRA), SUSY breaking is transmitted from a hidden sector through gravity. This reduces the number of free parameters to five in the minimal version of the model (mSUGRA). R-party is generally assumed to

[a]Along with SUSY, a new symmetry called R-parity has been introduced. Under this symmetry, standard model particles have eigenvalue 1 while sparticles have eigenvalue -1, so that the LSP is stable if R-parity is conserved.

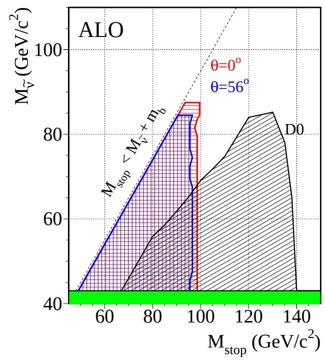

Fig. 5. LEP and DØ limits on stop and sneutrino masses assuming the stop decays to $bl\tilde{\nu}$ 100 % of the time.

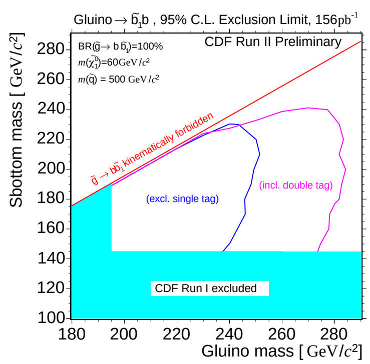

Fig. 6. CDF limits on gluino and sbottom masses assuming gluinos decay to a sbottom and bottom 100% of the time.

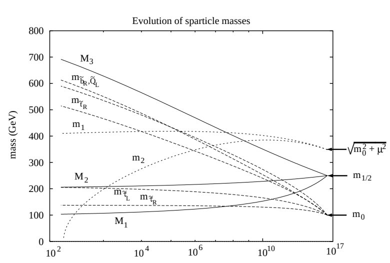

Fig. 7. Running of sparticle masses in minimal supergravity (mSUGRA). Note m_2 (μ^2), which is driven negative at low energy.

be conserved. This is the SUSY framework in which most searches are conducted. At the Tevatron, the golden signature for mSUGRA is the trilepton signature from

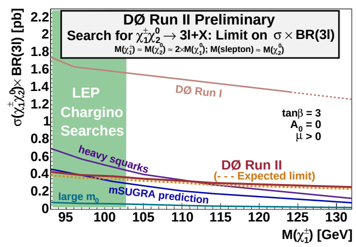

Fig. 8. DØ Run II limit on associated chargino-neutralino production and their decay to trileptons based on 147-249 pb^{-1} of data. The red curve denoted "DØ Run II" shows the cross-section limit from the analysis, while the purple, blue and green curves represent cross-section predictions in various models. Chargino masses with a predicted cross-section higher than the cross-section limit are excluded.

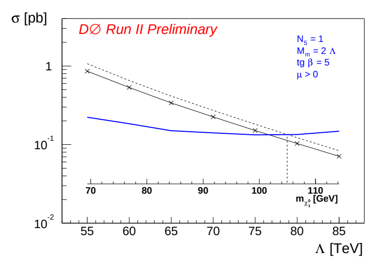

Fig. 9. DØ Run II limit on GMSB with a bino LSP. The parameter Λ is the supersymmetry scale in these types of models; the corresponding neutralino mass is also given.

associated production of $\chi_1^{\pm}\chi_2^0$ (the lightest chargino and next-to-lightest neutralino, respectively) and their decay through virtual sleptons and gauge bosons. The recent result from DØ shown in Figure 8 shows that the experiment's sensitivity is close to exceeding the range excluded by LEP.

Another extensively studied model of SUSY breaking is gauge mediated SUSY breaking, or GMSB. In this scenario, SUSY is also broken in a hidden sector, but the SUSY breaking messengers participate in standard model gauge interactions, and superpartner masses are therefore proportional to gauge boson couplings. The LSP is a very light (sub-eV) gravitino and the phenomenology is driven by the nature of the next-to-lightest supersymmetric particle (NLSP), which decays to its partner and the gravitino. This model's major support comes from the famous $ee\gamma\gamma\not{E}_T$ candidate event detected by CDF in Run I of the Tevatron [11]. In most instantiations of this model, the NLSP is either a slepton or the bino, partner of the unmixed B field in electroweak theory. At hadron colliders, the latter thus leads to signatures with two high-energy photons and missing transverse energy. The current best limit in this scenario is the recent result from DØ shown in Figure 9 [12].

In a supersymmetric world there are two Higgs doublets, and five physical Higgs bosons (versus one and one in the standard model). There are two charged Higgses

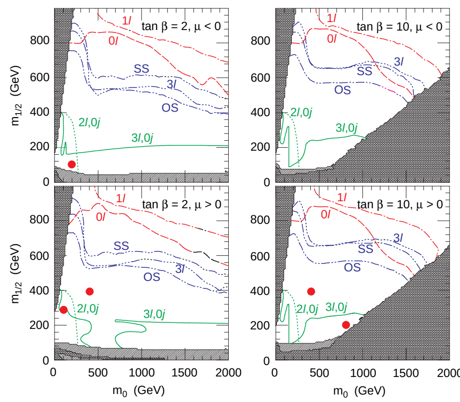

Fig. 10. Supersymmetry reach of the Atlas experiment in one year of low luminosity running (10 fb^{-1}) for various signatures, including lepton plus jets (denoted $1l$), jets plus missing transverse energy ($0l$), trileptons ($3l$), same- and opposite sign dileptons (SS and OS), etc. The four different plots correspond to different choices for two of the other mSUGRA parameters.

($H^{\pm}$), two CP-even Higgses (h and H) and one CP-odd Higgs (A). At the LHC, at least one of these can always be seen, although if m_A is large for much of the parameter space this Higgs is not distinguishable from the standard model Higgs. Luckily, in this region, other supersymmetric particles are often visible. Indeed, if the supersymmetry scale is less than about 1 TeV, supersymmetry should manifest itself through a plethora of signatures at the LHC. This is illustrated in Figure 10 [5] where ATLAS' sensitivity to mSUGRA is illustrated in various channels for one year of running at low luminosity (10 fb^{-1}).

Since in supersymmetry the LSP is usually expected to be stable, experiments will detect cascade decays of heavier particles, with the LSP detected through the presence of missing (transverse) energy. Therefore invariant masses cannot be reconstructed directly, and to determine sparticle masses the endpoints of kinematic distributions are used. If enough superpartners are accessible, then the pattern of sparticle masses can be measured and used to try to deduce the mechanism of SUSY breaking. At the LHC, it should be possible to measure the masses of the accessible fermion partners with $5-10$ GeV/c^2 accuracy, and this could be improved to 1 GeV/c^2 or better at the ILC [13]. Of course, this is very dependent on the actual spartner masses and the situation could be less favorable. Studies to determine the reach of both the LHC and ILC have been made, with one example illustrated in Figure 11 [14]. It is interesting to note that a 1 TeV ILC has sensitivity in the focus point area at large m_0 which is out of reach of the LHC.

In addition to direct searches for on-shell production of supersymmetric particles, rare decays and precision measurements can yield interesting data on SUSY parameters. Rare decays are processes in which the tree-level diagram is forbidden, for example because it is a flavor changing neutral current (FCNC). At the one loop level these often still involve a weak process, contributing further to keeping

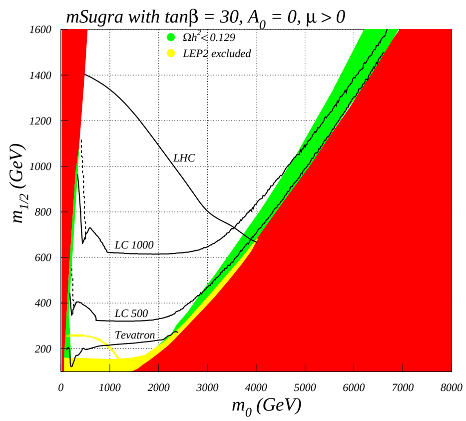

Fig. 11. Supersymmetry reach of the Tevatron, LHC and ILC with two different center-of-mass energies as a function of the mass parameters of mSugra for a particular choice of the other parameters. The red regions are theoretically excluded, while the yellow area has been excluded by LEP2. The green bands are the regions preferred by the WMAP dark matter measurement: at large $m_{1/2}$ but low m_0 the so-called coannihilation region, and at large m_0 the focus points where the LSP has a large higgsino component.

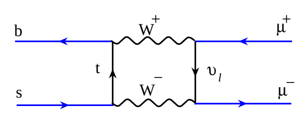

Fig. 12. One of the standard model box diagrams contributing to $B_s \to \mu^+\mu^-$ decays.

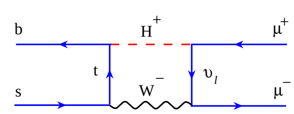

Fig. 13. A box diagram contributing to $B_s \to \mu^+\mu^-$ decays in two Higgs doublet models like for example SUSY.

the branching fraction low. If backgrounds from other processes are small, these can provide a means of probing physics at one or two loops. Other processes are measured with stunning precision, and can be calculated to similar accuracy, such that any (lack of) deviation can be interpreted in terms of new physics parameters.

A good example is the search for the decay $B_s \to \mu^+\mu^-$, for which the standard model branching fraction is expected to be [15] 3.8×10^{-9}. An example of a standard model diagram is given in Figure 12. SUSY diagrams like the one illustrated in Figure 13 could increase this value by up to three orders of magnitude. The Tevatron

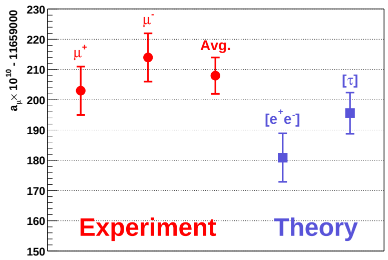

Fig. 14. Current experimental and theoretical values for the muon anomalous magnetic moment, from the E821 experiment

is currently the only copious source of B_s mesons and recent results from CDF [16] ($BR(B_s \to \mu^+\mu^-) < 5.8 \times 10^{-7}$) and DØ [17] ($BR(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-7}$) have been combined by M. Herndon [18] to yield[b] $BR(B_s \to \mu^+\mu^-) < 2.7 \times 10^{-7}$ at 95% C.L., an improvement of an order of magnitude over the earlier result.

Similarly, BABAR searches for $B_d \to l^+l^-$ decays. In 120 fb^{-1} of on- and off-resonance data [19] they set the following limits: $BR(B_d \to e^+e^-) < 6.1 \times 10^{-8}$ (standard model expectation is 1.9×10^{-15}), $BR(B_d \to \mu^+\mu^-) < 8.3 \times 10^{-8}$ (8.0×10^{-11}), $BR(B_d \to e^\pm\mu^\mp) < 18 \times 10^{-8}$ (0). This allows them to put a limit on the Higgs mass in the minimally constrained supersymmetric standard model at $m_H > 138\ GeV$ at 90% C.L. for $\tan\beta = 60$. Analogous analyses are done with the measurement of $B \to X_s\gamma$ or rare tau decays.

At Brookhaven, experiment E949 has recently observed another $K^+ \to \pi^+\nu\overline{\nu}$ candidate event, bringing their branching ratio measurement [20] to $BR(K^+ \to \pi^+\nu\overline{\nu}) = 1.47^{+1.30}_{-0.89} \times 10^{-10}$, whereas the current standard model estimate [21] is $BR^{SM} = 8.18 \pm 1.22 \times 10^{-11}$. The same authors [21] calculate that the SUSY contribution without R-parity violation can account for a maximum of 50% of the standard model value when taking into account the current SUSY bounds, and use this to set limits on some R-parity violating couplings that are the most stringent to date.

The measurement of the anomalous magnetic moment of the muon is a difficult, but well-understood experiment, now done to a stunning precision of 0.5 parts per million [22]. This means it is sensitive to two-loop corrections, and thus has great potential to see effects from heavy new particles. The theoretical value is correspondingly well known, to about 0.7 ppm. There is some variation in the calculations, however, and there are always two results, depending on which data is used as input for the corrections due to hadronic vacuum polarization. Figure 14 shows the experimental values for both muon charges and their average, as well as a theoretical calculation (with two results as discussed above). The discrepancy

[b]Since this combination was made, the DØ result shifted from $BR(B_s \to \mu^+\mu^-) < 4.6 \times 10^{-7}$ to $BR(B_s \to \mu^+\mu^-) < 5.0 \times 10^{-7}$ at 95% C.L. and the combined value is therefore expected to be slightly higher than quoted in the text.

between experiment and theory is two to three sigma, depending on which theoretical calculation is chosen, but the difference is always in the same direction. It should be noted that this discrepancy is larger than the effect of weak interactions by 30% , and it is therefore difficult to imagine that it's due to new physics in its entirety [23]. This situation makes it possible to set very stringent constraints on any new physics effects that would lead the theoretical result to pull even further from the experimental measurement. An example is given in Reference [24], where it is shown that a negative value of the parameter μ in the minimal supersymmetric standard model is now strongly disfavored.

4.2. *Technicolor*

While low-scale supersymmetry presents the advantages of solving the hierarchy problem, improving gauge coupling unification, and explaining mass, its prediction of the existence of elementary scalars and the fact that no evidence for SUSY has as yet been found, continue to inspire the development of alternate models. One of these is technicolor, a QCD-inspired, strongly coupled theory. In technicolor, the hierarchy between the electroweak and unification scales is explained as a confinement phenomenon of a new interaction, in analogy to the pion mass in QCD. Technifermions are bound into technihadrons, but there are no fundamental scalars. The strong technicolor coupling makes it difficult to satisfy the constraints from precision data, forcing increased complexity into the model, and we now have topcolor-assisted walking technicolor. Another unfortunate side effect of the strong coupling is that it makes calculations and therefore predictions difficult. At hadron colliders, it is thought that vector technimesons are most likely to be produced, and these then decay to technipions and longitudinally polarized vector bosons. The technipions act a like the Higgs boson and couple to mass, and are therefore expected to decay primarily to heavy quarks. Searches for technicolor at colliders are performed in the same final states as Higgs searches ($Wb\bar{b}$ at the Tevatron for example) and in dilepton final states [25].

4.3. *Extra Dimensions*

In the late 1990s, it was proposed [26] that the extra dimensions predicted by string theory could be quite large, and accessible at colliders. In the original ADD model, standard model particles are confined to a 3-brane with gravity propagating in more dimensions. The hierarchy problem[c] is solved by bringing down the fundamental Planck scale, which only appears high in three dimensions. In this model, there are two main types of signatures: on the one hand, interference from Kaluza-Klein graviton excitations [d] can visibly affect the high energy and angular behavior

[c]The large difference between the electroweak and Planck scales is commonly referred to as the hierarchy problem.

[d]Particles that propagate in compactified extra dimensions have quantified momenta in those dimensions, which appear as mass to the observer. Many of these particles, which have different

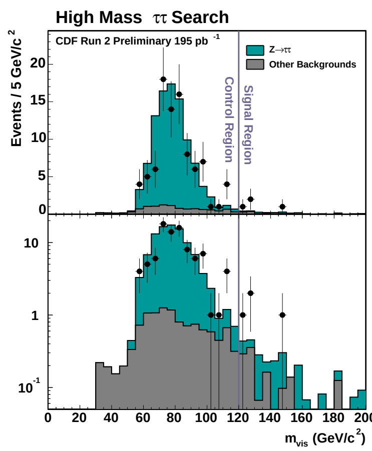

Fig. 15. Search for extra gauge bosons in the ditau channel at the CDF experiment: the plots show the visible ditau invariant mass for all candidate events, in both the control region below $m_{\tau\tau} < 120\ GeV/c^2$ and in the signal region above. This allows CDF to put a limit on a sequential Z' boson in this decay channel at approximatively $m_{Z'} \leq 400\ GeV/c^2$ at 95% C.L.

of standard model processes. This is because the graviton couples to the energy-momentum tensor, and at higher energies more and more excitations are accessible while the standard model cross-section typically falls fast. A second class of signatures comes from production of on-shell Kaluza-Klein graviton excitations, which then disappear back into the extra dimensions, leaving a missing energy signature. The current best limit on large extra dimensions in the ADD model was presented at this conference [27] and comes from the DØ experiment: $M_S > 1.43\ TeV$ at 95% C.L. in the GRW convention. The LHC is expected to be sensitive up to about $9\ TeV$ [28], depending on the number of dimensions.

4.4. *Resonances*

Many new physics models predict the existence of high mass resonances. This includes the warped extra dimensions model of Randall and Sundrum [29] and its variations, and Little Higgs and other models which exhibit extended group structures. The resonances themselves can be graviton excitations, gauge boson Kaluza-Klein excitations, or extra W', Z' gauge bosons with various coupling strengths and widths. Experimentally, analyses are done by final state and a single analysis is used to constrain many models. Figure 15 shows the invariant mass spectrum for ditau events in the CDF experiment. This distribution allows CDF to put a limit on a sequential Z' boson in this decay channel at approximativeky $m_{Z'} \leq 400\ GeV/c^2$ at 95% C.L. In Figure 16, the cross-section limit obtained by the DØ experiment in its search for Z' bosons decaying to e^+e^- is shown together

momenta in the extra dimensions, form a so-called “tower” of Kaluza-Klein excitations.

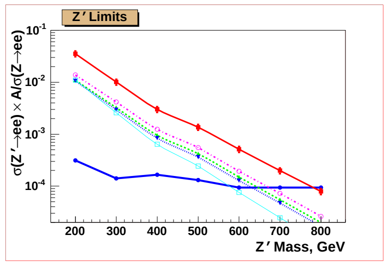

Fig. 16. Limits on extra gauge bosons from the DØ experiment. The blue line is the experimentally excluded cross-section, the red line the predicted cross section for a sequential Z' boson with couplings identical to the standard model Z boson, and the other lines represent production cross-sections for Z' bosons in various supersymmetric E_6 models.

with production cross-sections from various models. The limit derived for a sequential Z' is $m_{Z'} \leq 800\ GeV/c^2$ at 95% C.L.

If a new high-mass resonance is discovered, the distinction between a spin 1 and spin 2 particle can in principle be made by measuring the angle between one of the decay leptons and the beam direction in the dilepton center-of-mass frame [31], usually called θ^*. However, if parameters conspire, this may not be possible at a hadron collider [32], and in any case a linear collider would probably be necessary to distinguish between similar models by exploiting the lineshape [33].

At the LHC, resonances of mass up to almost 6 TeV/c^2 could be discovered provided the underlying model parameters are favorable. A linear collider would obviously be an ideal machine to study such a resonance, provided it is within its energy reach.

4.5. *Split Supersymmetry*

N. Arkani-Hamed and S. Dimopoulos recently proposed a model [34] in which they argue that the cosmological fine-tuning problem suggests that fine-tuning itself might be an intrinsic part of nature. This model therefore doesn't address the electroweak hierarchy problem, but mainly attempts to improve gauge unification over the standard model. This is achieved by keeping the scalars ultraheavy, but making the fermionic gauginos light through chiral symmetry. This has been baptised "split supersymmetry". The prediction for the Higgs mass is somewhat relaxed compared to low scale supersymmetry (to $m_H \lesssim 150\ GeV/c^2$), gauge coupling unification is achieved, the golden trilepton signature is still predicted since gauginos are light. While the model is new, the new feature in its phenomenology, a long-lived gluino, gives rise to signatures which are already searched for: an escaping neutral gluino hadron leads to the same monojet plus missing transverse energy predicted by ADD large extra dimensions, while charged gluino-hadrons would lead to charged massive particles which are searched for in the context of gauge-mediated supersymmetry breaking with a charged, long-lived NLSP. Results for both types of searches have been presented at this conference [35].

5. Direct Probes

Some of the fundamental question asked in section 2 can be investigated more-or-less directly, independently of a predictive model. A few examples are given here.

5.1. *Lepton Flavor Violation*

The generational structure of the standard model fermions clearly suggests that there is a link between the different generations. Therefore, lepton flavor violation is expected at some scale, and it is in fact seen in the neutrino sector over long distances. Experimentally, lepton flavor violating muon decays or conversions yield a very sensitive probe to high scale physics. In the search for $\mu \rightarrow e\gamma$ decays, the MEGA experiment has set a branching ratio limit at $< 1.2 \times 10^{-11}$ at 90% C.L. [36], with the MEG experiment [37] set to explore values down to 10^{-14}. Conversion of muons to electrons in in the Coulomb field of a nucleus $\mu N \rightarrow eN$ is a similar process which could be more sensitive depending on the physics process of lepton flavor violation. For this process, the current best limit is set by the SINDRUM II experiment [38] at $B_{\mu e} < 6.1 \times 10^{-13}$ at 90% C.L., and improvement by three orders of magnitude is expected from the MECO experiment [39].

5.2. *Proton Decay*

If there is indeed unification of quarks and leptons at some energy, then the proton is unstable. In fact, the non-observation of proton decay at this stage is already putting stringent constraints on a number of unification models, like minimal SUSY SU(5) GUT. The current limit on the proton lifetime is $\tau > 10^{31} - 10^{33}$ years [40] depending on the decay mode studied. In the next generation detector, which will most likely be a megaton water cherenkov detector, the sensitivity is expected to reach 10^{35} years, very close to the expectation of 10^{36} years from gauge coupling unification [41].

5.3. *Magnetic Monopoles*

In 1931 Dirac [42] demonstrated that the existence of even a single magnetic monopole would explain electric charge quantization. In most Grand Unification Theories (GUTs), magnetic monopoles appear, but with masses of the order of the unification scale. It is quite possible that much lighter monopoles exist and are produced in high energy colliders. Since magnetic charge is conserved, they are stable, and can be detected either as magnetic charges trapped in detector elements, as done by H1 [43], or as they travel through the detector. The latter method has been exploited by CDF to set the best limit to date on these particles, as shown in Figure 17.

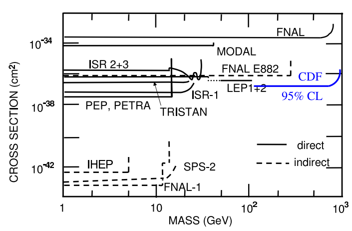

Fig. 17. 95% C.L. limit on magnetic monopole cross-section as a function of the particle mass.

6. Model Independent Searches

In addition to model-driven searches, there is an increase in so-called model-independent or general searches. In channels where backgrounds are sufficient small and/or understood it is indeed possible to achieve discrimination without resorting to sophisticated analysis of kinematic and topological distributions. A recent example comes from the H1 experiment [44], in which events are classified exclusively according to their final state, and the scalar sum of transverse momenta or invariant mass of final state particles are compared to expectation for each channel. These types of analyses have the added benefit of showing clearly that moderate excesses in a small number of channels are to be expected, just as in some channels the observed number of events is smaller than the prediction.

7. Current Experimental Hints

There is currently no conclusive evidence of any physics beyond the standard model, but there are of course some deviations from expectation. In addition to those described above, there is an interesting excess of events with isolated leptons at HERA. The total number of events with an isolated lepton and large missing transverse energy is in reasonable agreement with standard model predictions, but when in addition to that the recoil system is required to have large transverse momentum, a clear excess is seen in H1 [45]. For $p_T^X > 25\ GeV/c$ (where p_T^X is the transverse momentum of the recoil hadronic system), 5 and 6 events are observed in the electron and muon channels respectively, while 1.8 ± 0.3 and 1.7 ± 0.3 are expected, a 2.8 sigma effect. No excess is seen in those channels in ZEUS, but they observe [46] two events in the tau channel with 0.2 ± 0.05 expected. In a recent article [47], the compatibility of the two experimental results is investigated quantitatively with minimal model dependence. The authors conclude that the most plausible new physics explanation, anomalous tau production, has a probability of agreement with observation of a few percent. Anomalous single top or W boson production yield probabilities well below one percent.

8. Answering Fundamental Questions

Throughout this talk, some of the fundamental questions posed early on have been addressed:

- Understanding electroweak symmetry breaking, possibly through the discovery of supersymmetry, would explain mass.
- Understanding (the breaking of) grand unification will tell us about electric charge, color, and possibly spin. For this, both direct and indirect searches are critical to acquire knowledge of both low and high scale processes.
- Any manifestation of extra dimensions would lead to a much improved understanding of the structure of space-time.
- Information on GUT breaking, extra dimensions or CP violation will help understand why there are three generations (if that's the case).

9. Conclusions

There is as yet no convincing evidence of physics beyond the standard model, and care always needs to be exercised when anomalies are seen at the edge of an experiment's sensitivity. The good news, however, is that things would need to conspire for new physics to escape detection at the LHC. While the measurement of new physics parameters will start at the LHC, a linear collider with sufficient center-of-mass energy will be critical to the precise understanding of the underlying physics.

Among models of new physics, only supersymmetry deals with the hierarchy problem, gauge coupling unification and EWSB, but it comes at a significant price. It seems likely that most of the really fundamental questions, concerning for example the nature of electric and color charges, will remain unanswered for quite a while longer.

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